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13. ABSTRACT *(Maximum 200 words)*

The ram accelerator is a launcher concept conceived at the University of Washington that uses chemical energy to accelerate projectiles to hypervelocities, in principle up to 8 km/sec. The device is based on an in-bore ramjet concept in which a subcaliber projectile, shaped like the centerbody of a supersonic ramjet, is propelled down the center of a stationary tube filled with a pressurized propellant mixture of gaseous fuel and oxidizer. This propellant burns near the base of the moving projectile, generating thrust. The highest pressure in the system is always in the vicinity of the projectile base, rather than at the breech as in a gun, making for high propulsive efficiency. Under the subject grant the University of Washington has investigated various gasdynamic phenomena that govern the behavior and performance of the ram accelerator. These include the gasdynamic operating limits, low velocity starting phenomena, real gas effects at high pressures, superdetonative operation, and zero velocity start.

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INVESTIGATION OF REACTIVE GASDYNAMIC PHENOMENA IN THE RAM ACCELERATOR

RESEARCH ACCOMPLISHMENTS

Introduction and Overview

The ram accelerator is a new launcher concept conceived at the University of Washington that uses chemical energy to accelerate projectiles to hypersonic speeds, in principle up to 8 km/sec. The device is based on an in-bore ramjet concept (Fig. 1) in which a subcaliber projectile, shaped like the centerbody of a supersonic ramjet, is propelled down the center of a stationary tube filled with a pressurized propellant mixture of gaseous fuel and oxidizer. This propellant burns near the base of the moving projectile, generating thrust. The highest pressure in the system is always in the vicinity of the projectile base, rather than at the breech as in a gun. The chemical energy density and speed of sound of the propellant can be adjusted (via pressure and composition) to control the Mach number and acceleration history experienced by the projectile. Three different propulsive modes, centered on the Chapman-Jouguet (CJ) detonation speed of the propellant, have been experimentally observed. Projectiles have been accelerated smoothly from velocities below to above the CJ speed within a single propellant. During this process the nature and location of the combustion changes from thermally choked subsonic combustion behind the projectile to shock-induced supersonic combustion in the region between the projectile and the tube wall. The University of Washington ram accelerator facility has a test section of 38-mm bore and 16-m length. The ram accelerator is easily scalable for a variety of interesting applications including missile defense, long range bombardment, hypervelocity impact studies, hypersonics research, and direct launch of acceleration-insensitive payloads to orbit.

Under the subject grant the University of Washington has investigated a number of gasdynamic phenomena that govern the behavior and performance of the ram accelerator. These include the gasdynamic operating limits, superdetonative operation, zero velocity start, starting phenomena, real gas effects, etc. This report summarizes the research performed during the period of the grant, March 16, 1992 – December 31, 1997. Details of the research can be found in the publications listed at the end of this report.

Investigation of Ram Accelerator Operational Limits

Systematic experimental investigations of the regimes of heat release and Mach number in which the ram accelerator can operate were carried out in methane/oxygen/nitrogen and hydrogen/oxygen/methane propellant mixtures. Several distinct mechanisms were identified which limit the peak velocity that can be reached in a particular propellant mixture for the projectile configurations used in the investigations. Maximum and minimum propellant energy densities were determined by decreasing and increasing the diluent concentration until the immediate cessation of thrust was observed as the projectile entered the test mixture. Within these energy limits it was found that there is a relatively wide range of diluent concentrations that will accelerate the projectile beyond the Chapman-Jouguet (CJ) detonation speed of the

propellant mixture. These effects are readily seen by plotting the experimental results in the heat release-Mach number plane (Fig. 2). The projectile acceleration was almost always terminated by an unstart. The most energetic mixtures unstarted immediately with no observed projectile acceleration. The Mach number obtained in the test section increased to a maximum as the propellant energy was reduced. After reaching the optimal mixture, the unstart Mach number steadily decreased as the propellant energy was further reduced until combustion could no longer be supported. The phenomena which determine how the unstart Mach number depends on propellant energetics were the topics of this particular study. Propellant mixtures with less heat release than the optimum for peak Mach number were consistently found to unstart at velocities approximately 20% above the CJ speed. Variations in projectile geometry and materials were used to experimentally investigate the unstart mechanisms in this chemistry regime. The results indicated that the nose cone material has a significant effect on the unstart Mach number. Comparison of experiments in the two different types of propellant mixture confirmed that Mach number and heat release are the primary variables that determine ram accelerator performance.

Ram Accelerator Operation in the Superdetonative Velocity Regime

An investigation of superdetonative propulsive cycles was performed. Experiments with projectiles fabricated from aluminum and titanium alloys demonstrated that acceleration is possible at velocities greater than the Chapman-Jouguet (CJ) detonation speed of a gaseous propellant mixture. Projectile materials were found to play a significant role in these experiments. Theoretical modeling was successful in predicting projectile drag in nonreactive gas mixtures at hypersonic speeds. When this drag was subtracted from the ideal thrust of a supersonic combustion ram accelerator, the net thrust closely matched that measured in the experiments. The dependence of the maximum operating Mach number on both the projectile diameter and propellant heat release was examined. The peak velocity capability of the experimental projectile geometry is predicted to be about 1.5 times the CJ speed of the propellant mixture. It was found that the drag resulting from an increase in projectile diameter was more than offset by the corresponding enhancement in thrust, and that velocities of nearly twice the CJ speed are possible.

Numerical Analysis of Zero Velocity Start Technique for the Ram Accelerator

A method of accelerating a ram accelerator projectile from a position at rest to velocities greater than 1 km/s was modeled numerically. The proposed zero velocity start (ZVS) technique for a ram accelerator system uses combustion processes similar to those employed in conventional ram accelerator launchers. As with the existing ram accelerator concept, the projectile travels through a tube filled with premixed fuel and oxidizer. The crucial difference is that, while ram projectiles are currently injected into the combustible mixture at supersonic speeds to initiate combustion, this concept would require no initial projectile velocity. In the ZVS system, a diaphragm separates the propellant mixture from a tube segment containing the projectile and a low pressure gas. When the diaphragm is burst, a shock wave is generated and the flow accelerates. The expanding, high Mach number gas then passes over the projectile

(Fig. 3). Provided that combustion is initiated and the thermally choked ram accelerator propulsive mode can be established, the projectile accelerates into the expanding gas and eventually enters a quiescent propellant mixture. The results of this numerical study of the ZVS concept indicated that it has the potential to replace conventional gun-type prelaunchers for the ram accelerator without incurring significant penalties in barrel length or payload mass.

The Subdetonative Ram Accelerator Starting Process

The ram accelerator requires a conventional gun to initially boost the projectile to supersonic entrance velocity. Developing a robust starting process is instrumental for utilizing the ram accelerator in a variety of applications. Ongoing experimental investigations have continued to improve the understanding of transition from the conventional gun to the ram accelerator and initiation of the thermally choked propulsive mode, referred to as the starting process (Fig 4). Projectile start attempt experiments were used to explore the limits to successful starting, study the association of detonations with the wave unstart process, improve the understanding of the flowfield in the launch tube and ram accelerator tube, and investigate the effects of Mach number, propellant chemistry, obturator geometry and mass, and throat area variations on the starting process. The impossibility of performing a large number of detailed parametric experiments during this investigation precluded the generation of quantitative starting envelopes as yet, but a qualitative envelope was created that places the possible start outcomes relative to one another in a parameter space based on entrance Mach number and propellant composition (Fig 4). Increased propellant heat release, Q, is conducive to a wave unstart, while decreased Q eventually leads to a wave fall-off. Wave unstarts were found to occur at Mach numbers above and below successful starting conditions, and wave fall-offs were limited to Mach number below conditions which resulted in a successful start or wave unstart. Detonations were often observed in conjunction with wave unstarts, and for relatively high Q and Mach number these occurred immediately after entrance. Piston detonation experiments were also conducted to define detonation limits for several propellants, study the association of detonations with the wave unstart process, gain knowledge of the obturator dynamics as it transitions from the launch tube into the ram accelerator tube, and investigate the effects of obturator mass, obturator geometry, and launch tube air pressure variations on propellant ignition. Piston mass had a negligible effect on the detonation limits for the conditions studied. Solid pistons were able to initiate detonation at lower Mach numbers than perforated pistons. In addition, elevated launch tube pressure was found to increase the detonation limits. The piston detonation limits were found to not always be indicative of the upper velocity at which a ram accelerator projectile can be successfully started.

Effects of Launch Tube Shock Dynamics on Initiation of Ram Accelerator Operation

Normal operation of the University of Washington's ram accelerator involves the use of a perforated tube to vent gases from the light gas gun into an evacuated tank before the projectile enters the ram accelerator tubes. Because there is residual air in the launch tube and gases from the gun that blow by the obturator, a shock is generated and reflects between the moving projectile/obturator and the entrance diaphragm (Fig. 5). The vent tube perforations relieve the

resulting pressure rise, such that it does not become significant until after the projectile has passed the vent section. Experiments were performed to determine the feasibility of eliminating the venting process. It was found, as expected, that the pressure increase from the shock reflections was much higher for ventless operation than for vented operation and in some cases prevented initiation of the ram acceleration process. The effect of increasing residual launch tube pressure on the starting process of the ram accelerator was also investigated. It was found that for initial gun launch tube pressures of 21~kPa or less, successful starting of the ram accelerator was possible at a fill pressure of 50 atm.

High Acceleration Experiments Using a Multi-Stage Ram Accelerator

Methods of maximizing projectile acceleration to obtain high velocities with the thermally choked ram accelerator were investigated. A low mass (50 gm) projectile geometry was developed that can be reliably accelerated up to the Chapman-Jouguet detonation speed of the propellant in a 38 mm bore ram accelerator. Experiments were performed in $CH_4/O_2/He$ propellants, wherein Mach number and heat release of combustion were varied to obtain very high projectile acceleration (Fig. 6). Using 50 atm fill pressure in a 2-m long first stage, average accelerations of over 38,000 g were routinely achieved, allowing the projectile to be accelerated from 1320 to 1800 m/s. Two and three-stage ram accelerator investigations culminated in a staging configuration that produced an average acceleration of ~35,000 g over three 2-m long stages, resulting in a peak velocity of 2404 m/s in a distance of only 6 m.

Real Gas Effects on Thermally Choked Ram Accelerator Performance

A one-dimensional performance analysis code has been modified to account for real gas effects in the combustion zone of the thermally choked ram accelerator. Previous computational studies utilized the ideal gas equation of state and underpredicted experimentally measured thrust values as a function of Mach number. The post-combustion pressure in the ram accelerator is on the order of a few hundred bar and in this regime it is no longer appropriate to ignore intermolecular interactions. Including a compressibility factor to account for these real gas effects provides a much better match with experimental data. The current research code incorporates the following equations of state: ideal gas, Boltzmann, Percus-Yevick, and a direct solution to the virial expansion in which the virial coefficients are computed using the Lennard-Jones and Stockmayer potentials. The ideal gas equation of state performs well for initial fill pressures up to 10 bar, while the Boltzmann and direct virial model perform adequately for fill pressures up to 50 bar. The Percus-Yevick model also performs well for ram accelerator fill pressures up to 50 bar and is expected to accurately model fill pressures up to a few hundred bar. These results are summarized in Fig. 7.

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Gilbert Chew, PhD, June 1995
Thomas Imrich, M.S.A.A., June 1995
Andrew Higgins, PhD, December 1996
Eric Schultz, M.S.A.A., March 1997
Joshua Elvander, M.S.A.A., June 1997
Jesse Stewart, M.S.A.A., June 1997
David Buckwalter, PhD in progress
Christopher Bundy, PhD in progress

REPORTABLE INVENTIONS

None

PUBLICATIONS

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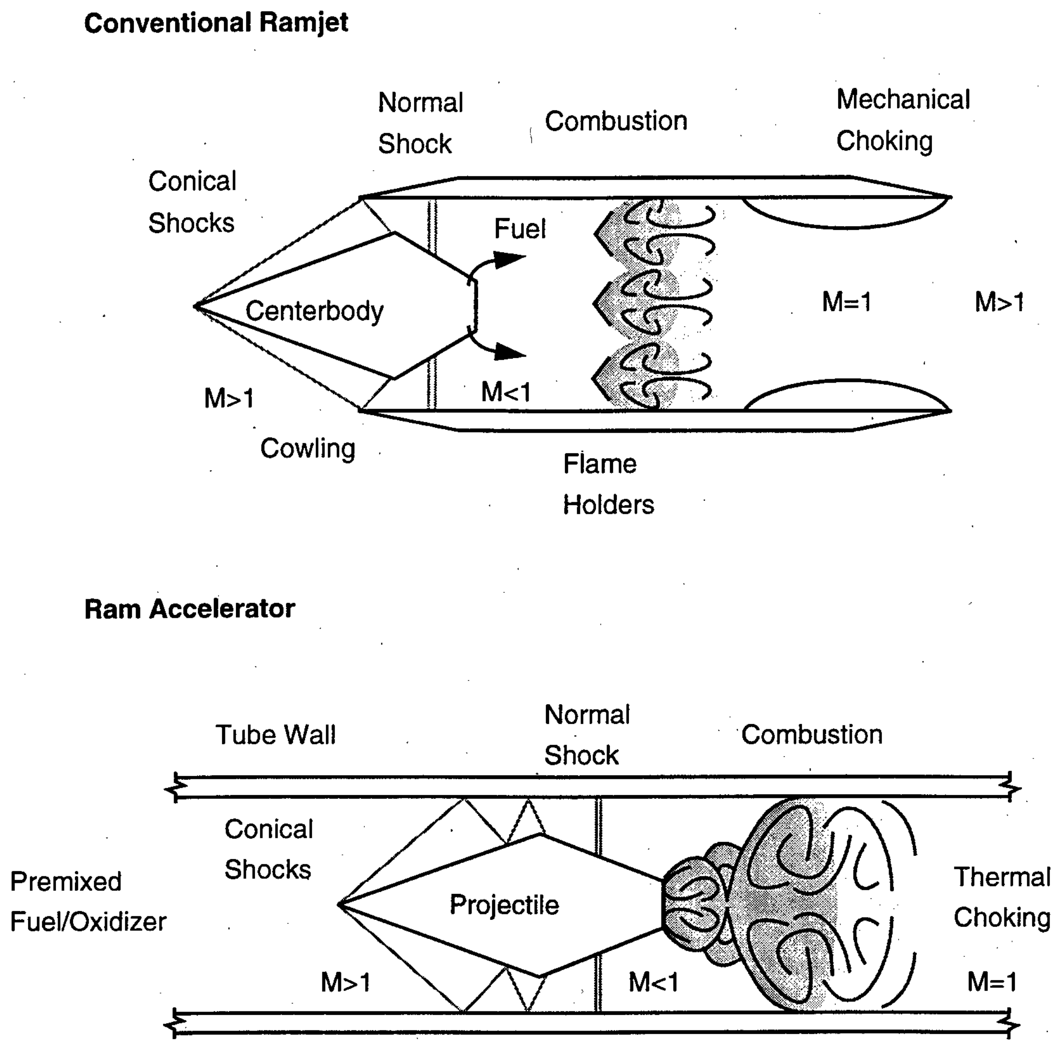

Fig. 1 Comparison of ram accelerator and conventional ramjet.

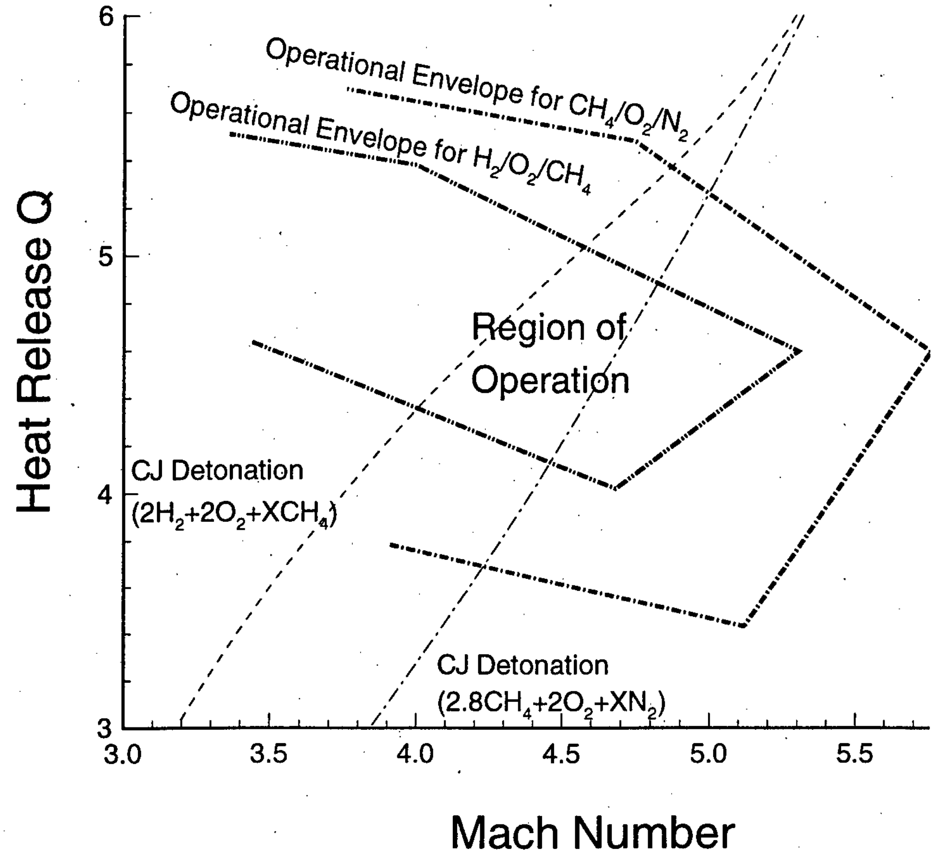

Fig. 2 Operational envelope of the ram accelerator.

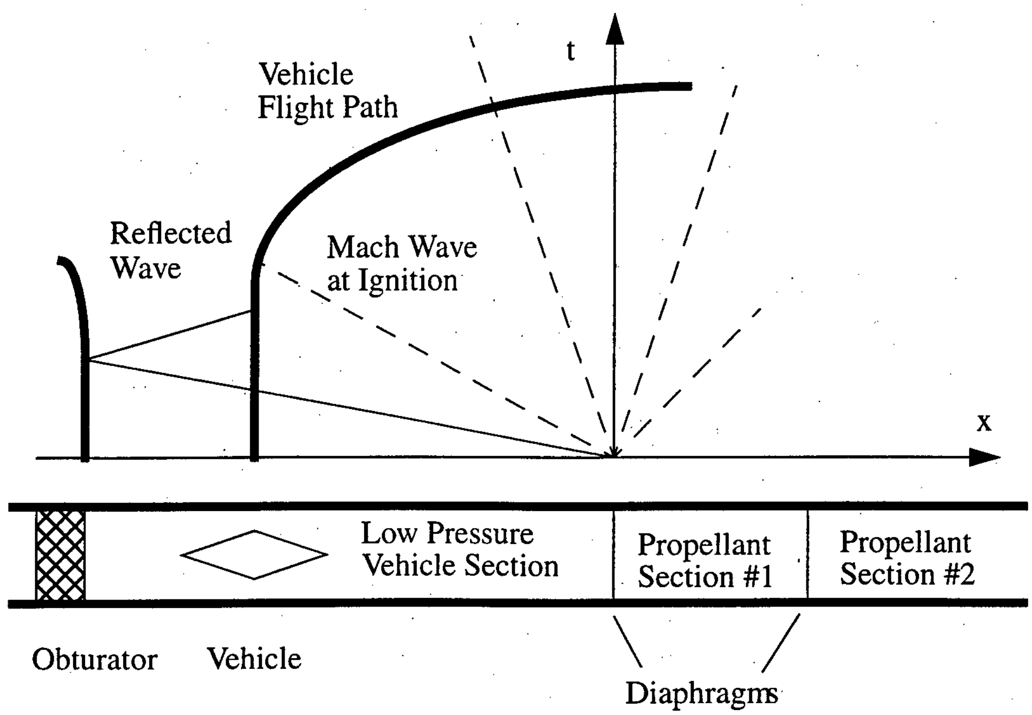

Fig. 3 Zero velocity start technique.

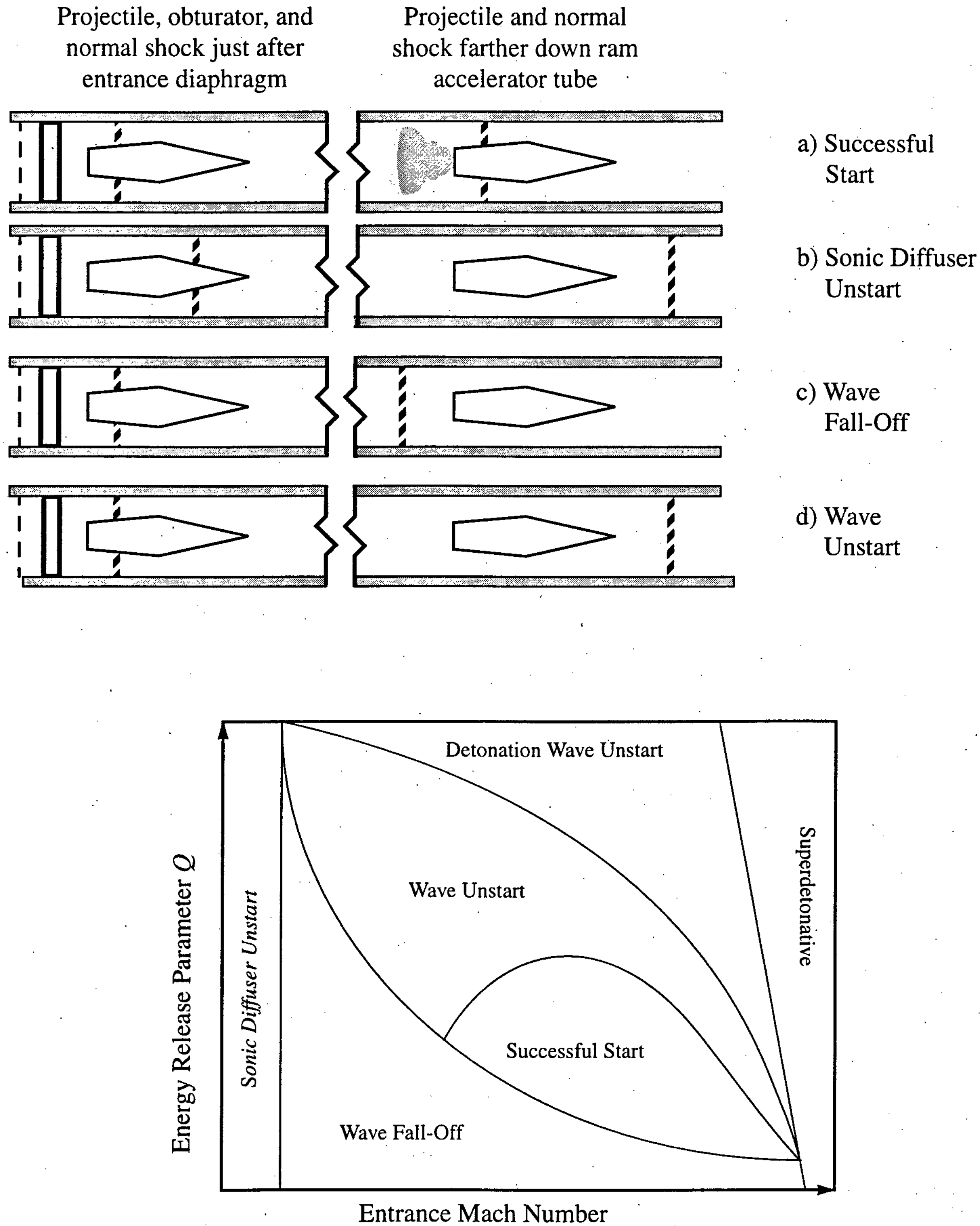

Fig. 4 Outcome of start attempts and generalized ram accelerator starting envelope.

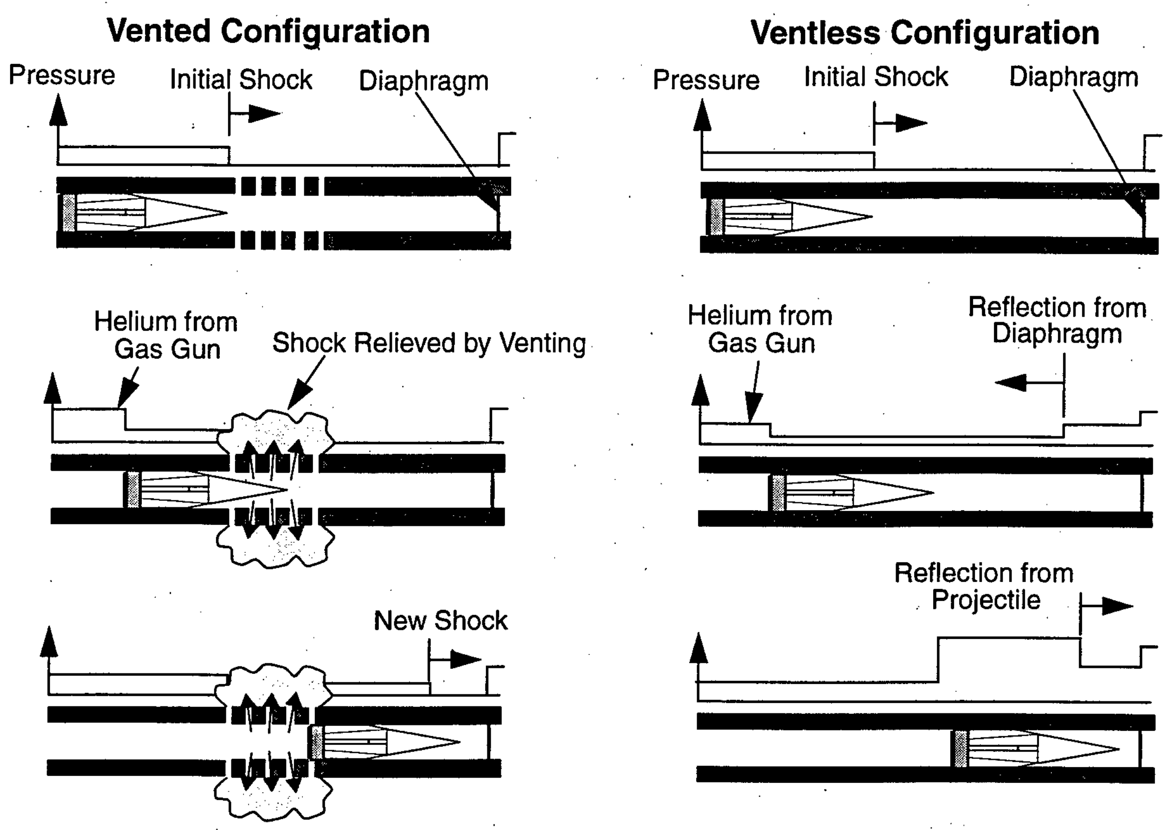

Fig. 5 Ram accelerator starting process; with and without venting.

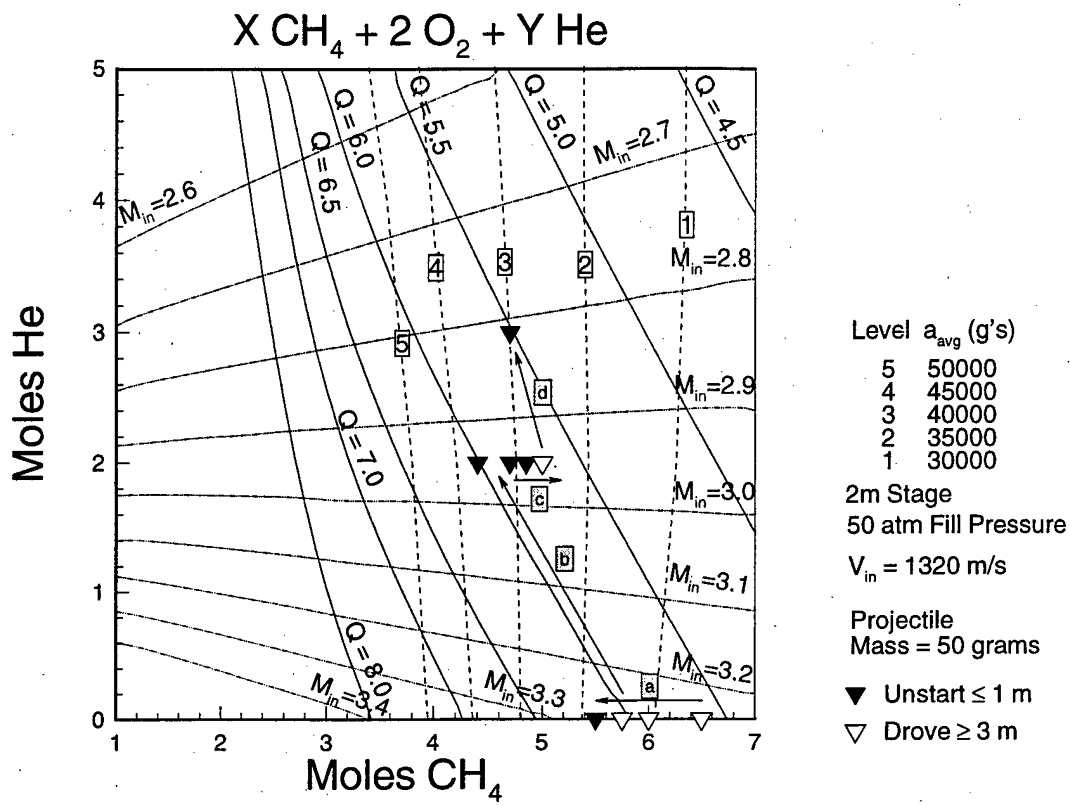

Fig. 6 Mixture map for optimization of projectile acceleration.

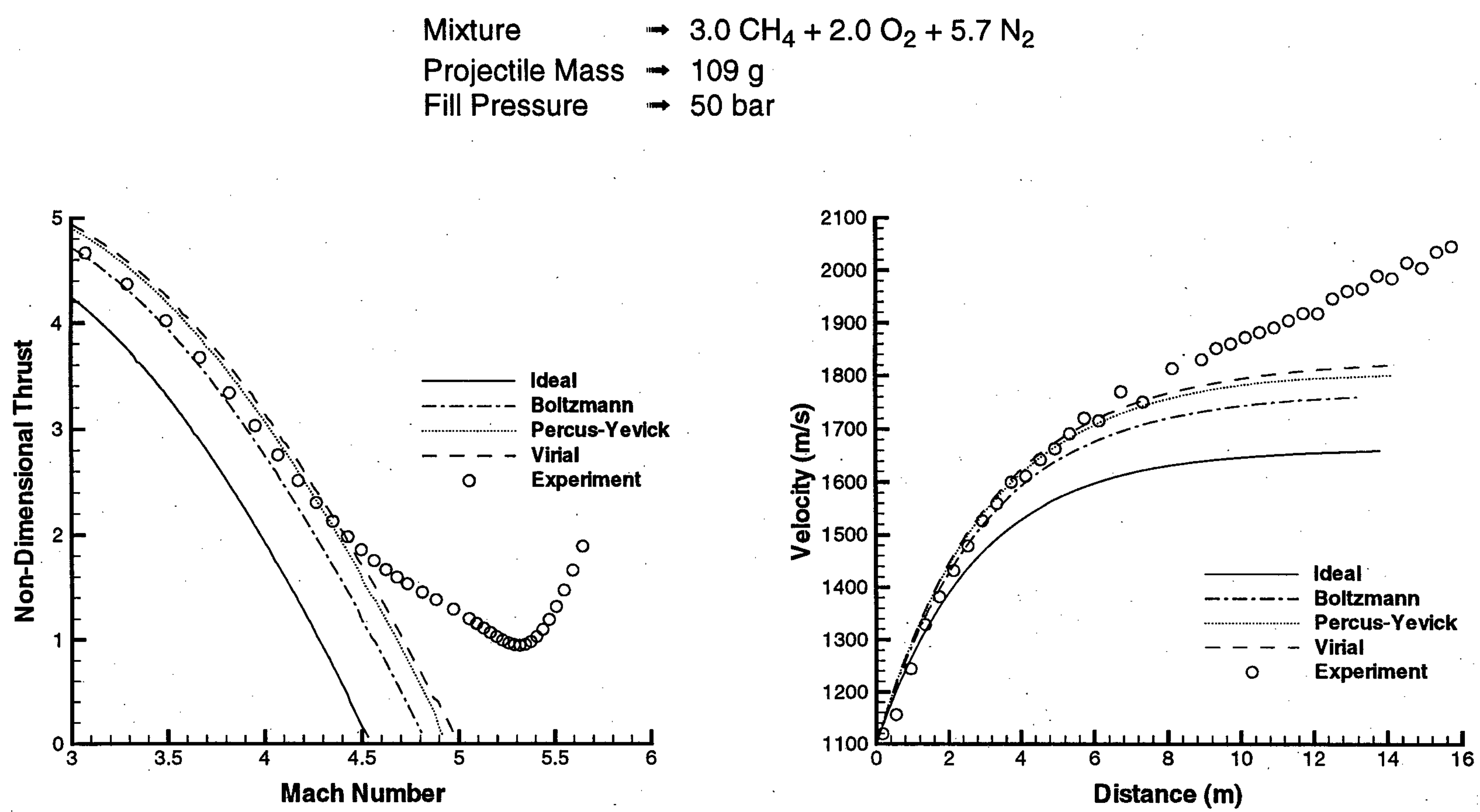

Fig. 7 Real gas effects on ram accelerator performance.